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UNITED STATES NAVY

PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

1 JANUARY 1947

CORNELL
AERONAUTICAL LABORATORY

SEMI-ANNUAL PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-119, TASK ORDER I

CORNELL AERONAUTICAL LABORATORY
BUFFALO, NEW YORK
1 JANUARY 1947

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INTRODUCTION

This report is the first of a series of summary reports on Project SQUID. Specifically, the scope of this report includes all work accomplished from June 10, 1946, the date on which Cornell Aeronautical Laboratory was formally authorized to begin work on Project SQUID, to January 1, 1947. The work was authorized under Contract No. N6ori-119, Task Order No. 1.

All work on Project SQUID at Cornell Aeronautical Laboratory has been carried out under three phase assignments.

Phase 1. In connection with pulsating jet engines: to undertake theoretical and wind tunnel investigations on flows and losses in diffuser inlets, diffusers, intake valves, exhaust nozzles, and thrust-augmenting ducts for subsonic and supersonic pulsating jets.

Phase 2. In connection with pulsating jet engines: to study the theory of combustion, the effect of turbulence on flame propagation and cooling, and to verify and augment existing theories by means of experimental investigation of ignition, combustion, flame holding, flame propagation, and cooling.

Phase 3. In connection with pulsating jet engines: to undertake experimental investigation of temperature and fatigue-resistant materials for intake valves and coatings and of fabrication methods and techniques to cover said material.

PULSE JET THEORY

An attempt is being made to study the mechanism of a pulse jet by means of analogous physical phenomena. By introducing concepts from other fields, new approaches to the problem may suggest themselves, and it should also be possible to carry out model experiments which permit the study of the influence of various parameters in an easier way than by working with actual jets. In order to gain confidence in these methods, a start should be made with the investigation of comparatively simple problems where some check on the results is possible. This program is still in a very early stage. At first the electrical analogy was studied. Here, gas flow in pipes is compared with flow of electricity in transmission lines. However, while the acoustical case can very well be represented by a corresponding linear electrical system, no way has been found to represent the gas oscillations of large amplitudes which occur in a jet by a corresponding non-linear electrical system. No further work on this analogy is being done at the present time. The other approach which is being considered is the analogy of pressure waves in a gas flow and surface gravity waves in an open water channel. Within certain limitations, this analogy is very far reaching and it is hoped that valuable information will be obtained by this method.

In theoretical investigations of the pulse jet by N. P. Bailey and H. A. Wilson, the conclusion is drawn that a shortening of the combustion time would result in a considerable improvement of performance. An arbitrary function for the rise of temperature was assumed, and the combustion time was defined as that time in which temperature of the burning gas reaches 95 per cent of the maximum temperature. The theory is in fairly good agreement with experiments if a combustion time of about 0.020 sec. is assumed. The results of the theory were analyzed to find whether there was any optimum combustion time to produce maximum thrust. This was found to be about 0.0025 sec., and the thrust developed was then about three times as large as with present combustion times. This maximum is not very sharp, so that the optimum time does not appear to be very critical. In view of the simplifying assumptions of the theory (uniform temperature and pressure rise throughout the whole combustion chamber, assumption of constant bulk modulus of elasticity, which is actually proportional to pressure, arbitrary definition of temperature rise, and combustion time), the actual numerical values have only limited significance, but the general conclusion might hold that a very considerable improvement of performance may be expected if the combustion time can be reduced to a fraction—perhaps one-eighth—of the present values.

AERODYNAMIC STUDIES

Two-dimensional diffuser models have been tested in the Cornell Aeronautical Laboratory supersonic wind tunnel at a Mach number of 1.7, and schlieren photographs have been made of the shock pattern as shown in Figure 1. Static and stagnation pressure measurements have also been made at various points of the duct. Experimentation has been started, on the same diffusers, employing fluctuating back pressure to simulate the condition of intermittent combustion. A butterfly valve at the outlet is being used to obtain pressure fluctuations of the desired frequency and amplitude. An attempt has been made to improve the technique for high speed motion picture recording of the shock pattern in the unsteady-flow condition.

Plans are underway to extend the above experimentation to include a pressure survey on the external surface of the ducted body in the unsteady condition of spill-over with pulsating back pressure. Meanwhile, two-dimensional supersonic wind tunnel tests have been conducted on blunt and sharp wedges, simulating the external surfaces of ducted bodies with and without steady spill-over from the duct entrance. The results of these tests indicate that the effect of steady spill-over is to increase the wave drag over most of the external surface, but to decrease it in a narrow region around the lip. Concurrently with the pressure measurements, schlieren observations have been made which reveal the presence of a region of intense expansion immediately following the detached shock. This expansion culminates in a second shock a short distance aft of the lip as shown in Figure 2.

Figure 1. Shock pattern in a two-dimensional diffuser at M=1.7.

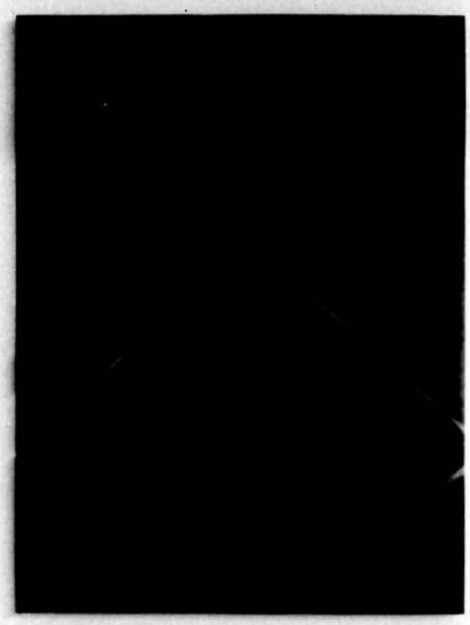

Figure 2. Shock pattern around a blunt-edged spill-over. Simulator at M=1.7.

COMBUSTION STUDIES

An experimental investigation has been started to determine the influence of different parameters affecting the velocity of flame propagation. The main aim is to investigate the influence of turbulence under controlled conditions of temperature, air/fuel ratio, and pressure.

In order to overcome the difficulties involved in controlling the various parameters in a steady flow, the investigation is being made in a container filled with the combustible mixture. This container, or combustion chamber, is made of a 2-foot-long, 6-inch-diameter pyrex pipe as shown in Figure 3. It is important that the pressure in the chamber be the same as the ambient pressure in order to prevent a sharp drop or building up of pressure when the chamber ends are opened at the time of ignition.

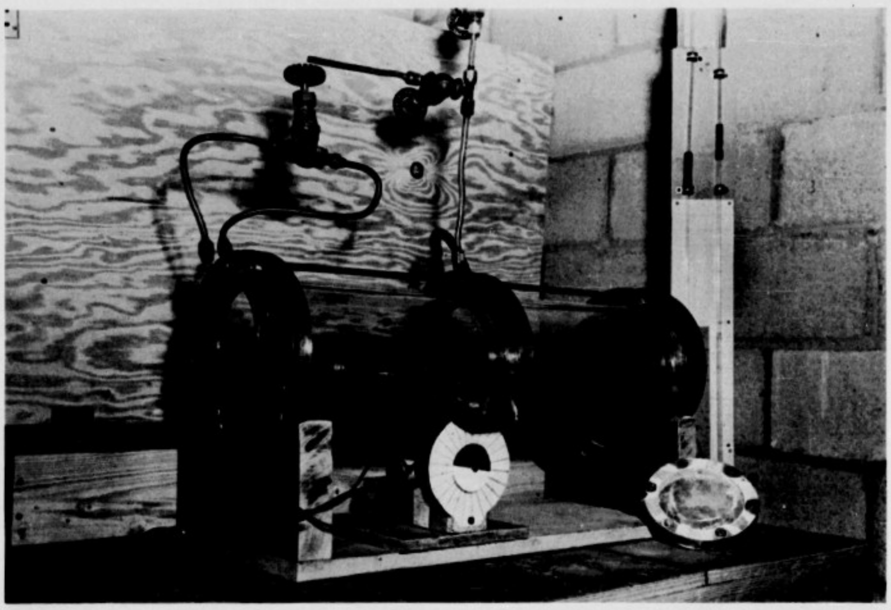

Figure 3. Pyrex combustion chamber.

This makes it possible to close the chamber with aluminum foils which break under a static-pressure differential of only about 4 mm. H_2O. The chamber is partly evacuated, and the gaseous fuel is added until the pressure is brought back to that of the surrounding atmosphere. The amount of evacuation is the partial pressure of the fuel in the mixture with the chosen air/fuel ratio.

After the mixture is introduced, the temperature may be brought to any desired value by means of refrigerating or heating coils. For experiments at pressures other than atmospheric, it is necessary to place the combustion chamber inside a large pressurized container. The Cornell Aeronautical Laboratory altitude chamber may be used as a container for experimentation at pressures below atmospheric. To simulate the flow condition of the mixture relative to an ignition point, a spark will be moved along the chamber at a controlled speed. To eliminate any flow disturbance which may be caused by moving bodies or surfaces in the chamber, the spark will be made to occur between two parallel electrodes and will be moved by means of a magnetic field at a right angle to the spark. Figure 4 shows the electric circuit for the high-tension supply (where the resistance R is adjusted to give optimum results) and Figure 5 shows the setup of the elec-

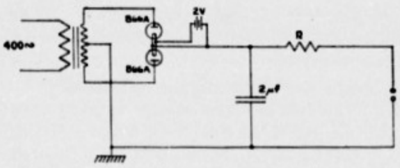

Figure 4. Circuit of high tension supply for the spark.

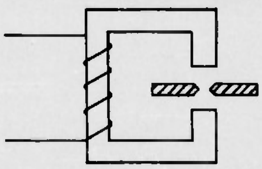

Figure 5. Moving spark device, relative arrangement of electrodes and magnets.

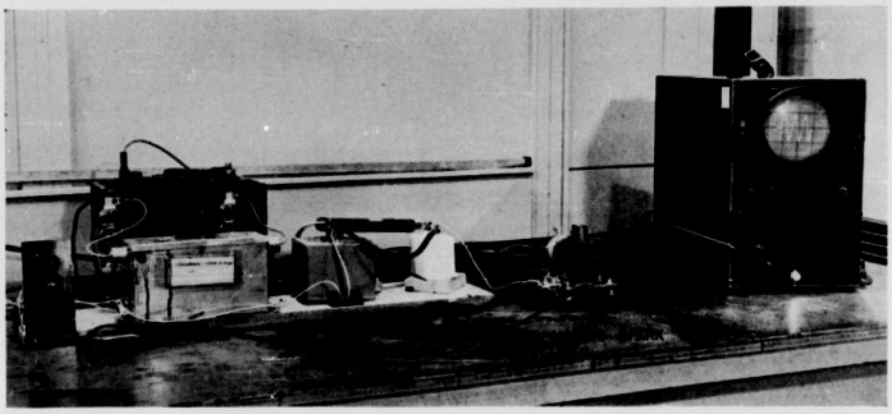

Figure 6. Moving spark device and high tension supply.

trodes and the magnet. A photograph of a moving-spark device used for preliminary experimentation is shown in Figure 6.

A high-speed moving picture technique for recording the flame pattern and velocity is being perfected. In order to increase the luminosity of the flame and permit extremely short exposures, a sodium compound will be introduced into the chamber by blowing in air through a mixing chamber containing such a compound (shown in Figure 3) before introducing the fuel into the combustion chamber. A sample of a high speed motion picture recording of flame propagation is shown in Figure 7. In this particular experiment, the spark was not moved and ignition took place at one end point.

The recorded slope and shape of the flame front will be used to establish the flame velocity under various conditions and the effect of localized disturbances upon such velocity.

A program of experiments has been planned to determine means for obtaining very high velocities of propagation of flames in tubes. In particular it is intended to investigate how various types of constrictions or wall disturbances in the tube produce very high burning velocities, and to find whether those velocities once reached are or can be maintained. If they can be maintained, the combustion time in pulsating jets could be regulated in this way.

The experimental setup, which is nearly completed, is essentially a 2½-inch I.D. steel tube 12 feet long. It is made up of sections 2 feet long to permit easy variations of experimental conditions. The tube will be filled by making both ends airtight, evacuating to a proper extent, and refilling the tube with a gaseous fuel to atmospheric pressure. Before igniting the mixture with a spark, one or both ends will be opened. Figure 8 is a photograph of one of the end sections, showing the mechanism which keeps the tube closed until immediately before firing. Some of the constriction rings and spacers are shown in front of the tube. It is intended to use different sizes and various numbers and spacings for the constrictors.

The velocity of flame propagation will be measured in the following way: A number of small gaps (about 1 mm.) between two wires insulated from each other will be mounted along the tube. Two of them are shown in Figure 8; one is shown mounted in normal position and the other is shown disassembled. Passage of the flame front, and resulting ionization of the gap will be used to measure the flame velocity by measuring the travel time between the gaps. The principle of the circuit is shown in Figure 9. The oscillograph records the voltage across the gap. As a result of ionization due to the high resistance *R* (about 10 Megohms), voltage drops as soon as current flows. Placing the gaps parallel to the oscillograph (instead of in series) has two advantages, both of which tend to reduce pickup of outside interference:

1. One side of the gap can be grounded.
2. The full oscillator voltage appears across the gap (before the flame front reaches it), and the necessary amplification at the oscillograph is therefore small.

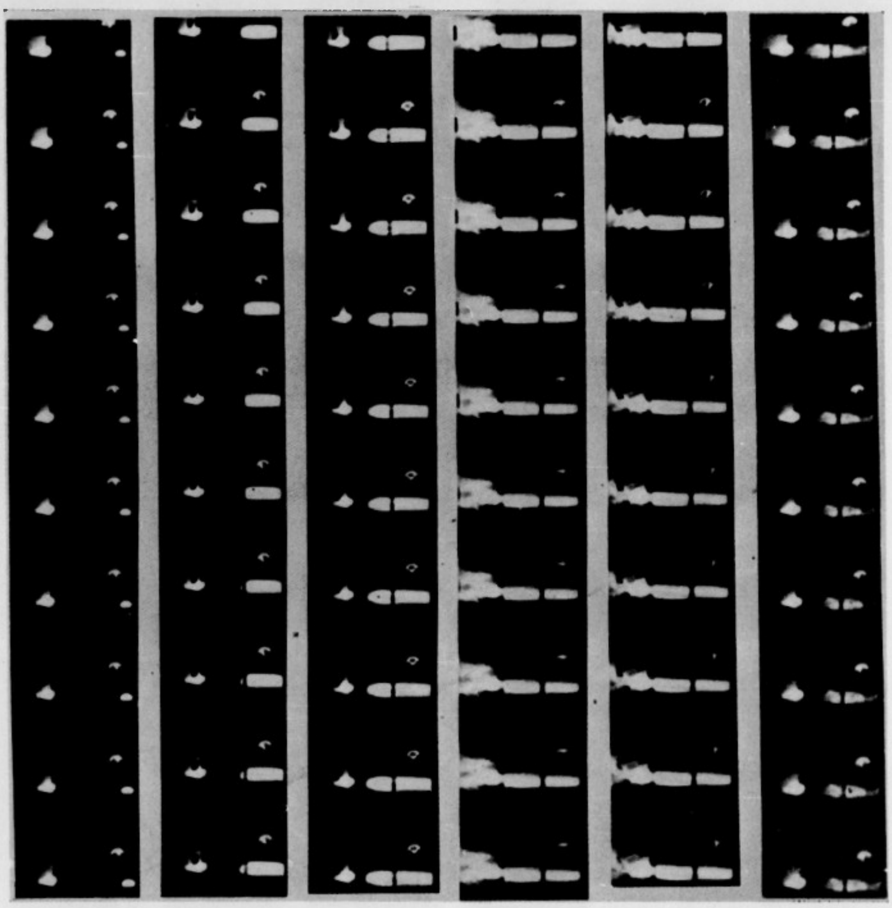

Figure 7. Combustion in the pyrex chamber. Stoichometric city gas mixture colored with sodium and photographed at 2,900 frames per second, Kodak Super-XX Panchromatic Film, lens f/2. On the second and third strip note the aluminum foil being blown out.

A number of waves show on the screen, and whenever the flame reaches a gap, the amplitude will be greatly reduced because of the voltage drop in *R*. The frequency of the oscillator is selected to provide a suitable time scale. The oscillograph operates in "single sweep" connection. Ignition of the gas mixture will start the sweep, and a photograph is taken of the screen. The method was tested by rotating an ionization gap in such a manner that it touched a flame once during each revolution. The velocity of the gap could be measured on the oscillograph and compared with the known speed of revolution of the driving motor. Good agreement of these values was obtained.

Experiments were begun on gas sampling for the purpose of developing methods for measuring both

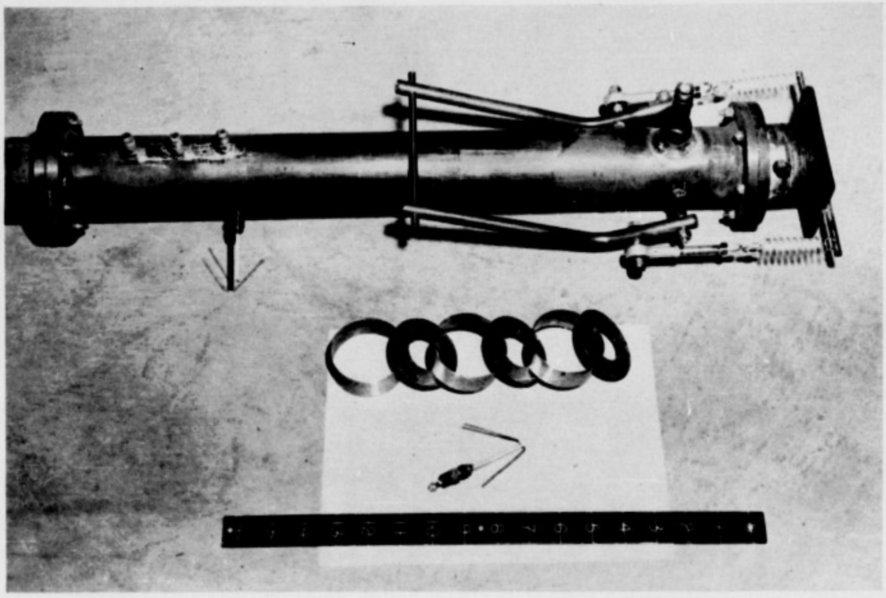

Figure 8. End section of combustion tube.

the amount of heat release in combustion (in a given volume of mixture) and the total time and variation with time of such heat release.

The method of sampling under development is not intended as a substitute for spectroscopic methods. Rather, it is intended as a rough practical tool which can be used in the evaluation of any burner or combustion condition. In order to develop aeropulse devices which are efficient from the chemical standpoint it is necessary to control combustion conditions so that there is a maximum amount of thermal energy released per unit quantity of fuel during the combustion process, and to control the heat release so that a maximum thrust (averaged over a cycle) is obtained per unit quantity of fuel. The thermal efficiencies previously reported for the aeropulse have been low. Thus the necessity of a method, such as the gas-sampling method proposed, for determining thermal combustion efficiency becomes obvious. The assumption is made in the application of the proposed gas-sampling method that all of the important energy losses which would decrease the combustion efficiency can be calculated from the gas-sampling data. In other words, it is assumed that extremely unstable combustion intermediate products, such as free radicals, have so short a life that they react to form stable products before the burned gas leaves the combustion chamber. It is thus assumed that the reaction of these extremely unstable products to form stable products during the cooling in the sampling tube would cause no great error in the calculation of combustion efficiency.

Interesting results were obtained from the application of heat transfer equations to a gas passing through a cooled tube of small diameter. Application of the analogy between fluid friction and heat transfer, and of the equation for fluid friction in small tubes, yields the equation

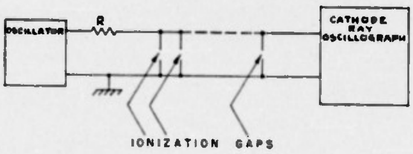

Figure 9. Principal circuit for ionization gaps.

$$\frac{dt}{(t-t_w)} = \frac{32\mu}{D^2\rho}\,d\theta$$

in which t is the gas temperature, t_w the wall temperature, μ the gas viscosity, ρ gas density, D tube diameter, and θ time. Thus the time of cooling is independent of the rate of flow and proportional to the square of the diameter. This equation was solved (with wall temperature at 100°F.) for stainless steel tubing 0.02 inch in diameter. The solution yielded the following time intervals for a gas with viscosity and density such as CO_2:

Cooling Range, °R	Time, Milliseconds
4,000 to 3,000	11.5
3,000 to 2,000	34.7
2,000 to 1,500	45.2
1,500 to 1,000	204.9

Since there were insufficient data available on the speeds of the reactions of the oxidation of C_n and H_2 to determine the extent to which these reactions would occur in the time-temperature intervals listed above, experimental measurements were attempted.

For this purpose, a triple-walled sampling tube was fabricated using 0.02-inch I.D. stainless steel tubing in the center, with water flowing in the annular spaces surrounding it. While a colder fluid than water might have been used as the cooling medium, it is obvious that this would not produce much greater cooling speed except in the final stages where reaction rate is probably negligible.

This sampling tube has been tested qualitatively by withdrawing samples from a blast-lamp flame that was enclosed in a space surrounded by fire brick. The fire brick was heated to 3,300°F. Significant quantities of C_n, H_2 and O_2 were found in the sample.

Quantitative tests are now being tried in which CO_2 and H_2O are heated to high temperatures. Samples are then collected and analyzed, and the results are compared with the amount of decomposition calculated from thermodynamic equilibrium data. But since temperatures in excess of 3,000°F. are required for this, difficulty has been encountered in heating gases to these high temperatures because of limitations of materials. Small furnaces constructed from porcelain crucibles were quickly fused.

To solve this problem, samples of CO_2 were decomposed in an electric arc by passing the gas slowly through a hole drilled longitudinally through the axis of a steel negative electrode. Samples were withdrawn as the gas passed through the arc. A Dietert multi-source power unit supplied a d-c arc current of 3 amperes. The gas samples showed that the amounts of CO and O_2 were in approximate agreement with the percentage of decomposition which might be expected at the probable temperature attained in the arc, but this temperature could not be determined exactly.

A furnace is now being constructed in which temperatures can be measured. This furnace will have a 3-inch-diameter gas-air flame which can be enriched with oxygen. Two methods for decomposing the gas samples are being studied. By one method, a carbon tube containing the gas to be decomposed thermally will be heated and its temperature determined by an optical pyrometer; by the other method, the carbon tube will be heated by passing electricity through it. In conjunction with this experimental work, the availability of tungsten and molybdenum as substitute tube-materials is being investigated.

METALLURGICAL STUDIES

In general the metallurgical program covers an experimental investigation of heat-resistant materials for use as flutter valves. The most important metallurgical property for this application is the fatigue life of the metal at elevated temperatures. Other properties such as strength, vibration and shock resistance, and corrosion and erosion characteristics at elevated temperatures are also important and will be investigated. Fundamental data will be established to explain the high-temperature characteristics of the alloys. This will be accomplished by means of high-temperature metallography and X-ray diffraction methods. The final phase of the material investigation will be the formulation and development of new alloys suitable for use at the high temperatures necessary in the operation of pulse jets and particularly applicable to flutter valves and their operation. It is believed that this final phase of the work can only be approached by first completing the high-temperature metallurgical investigation now being done.

A literature survey on high-temperature metallography was made and a bibliography prepared. The literature describes procedures for the observation of specimens, heated in vacuo and in controlled atmosphere, at magnifications of 200× and at temperatures up to 1,200°C.

The conditions under which the valve material must operate in the pulse jet have been investigated. An experimental program for evaluating suitable valve material in terms of vibration life versus temperature has been started. A new type of fatigue-testing machine is being considered for use. It operates on the pneumatic resonant principle and would be used to vibrate specimens at their natural frequency while at elevated temperatures.

A high-temperatore metaloscope is being developed for the metallographic study of metals under vibration and fatigue. The two main parts of such a metaloscope are the optical system and the furnace used for holding the specimen. The details of the proposed metaloscope are given in Figure 10.

The principle of heating a metallic specimen or object by means of an induced high-frequency electromagnetic field will be investigated as a possible heat source for the proposed high-temperature metaloscope. A Tocco Jr. 15 kw. induction-hardening machine will be used both for the investigation of temperature of the specimen versus time and for the temperature of the specimen and the surround-

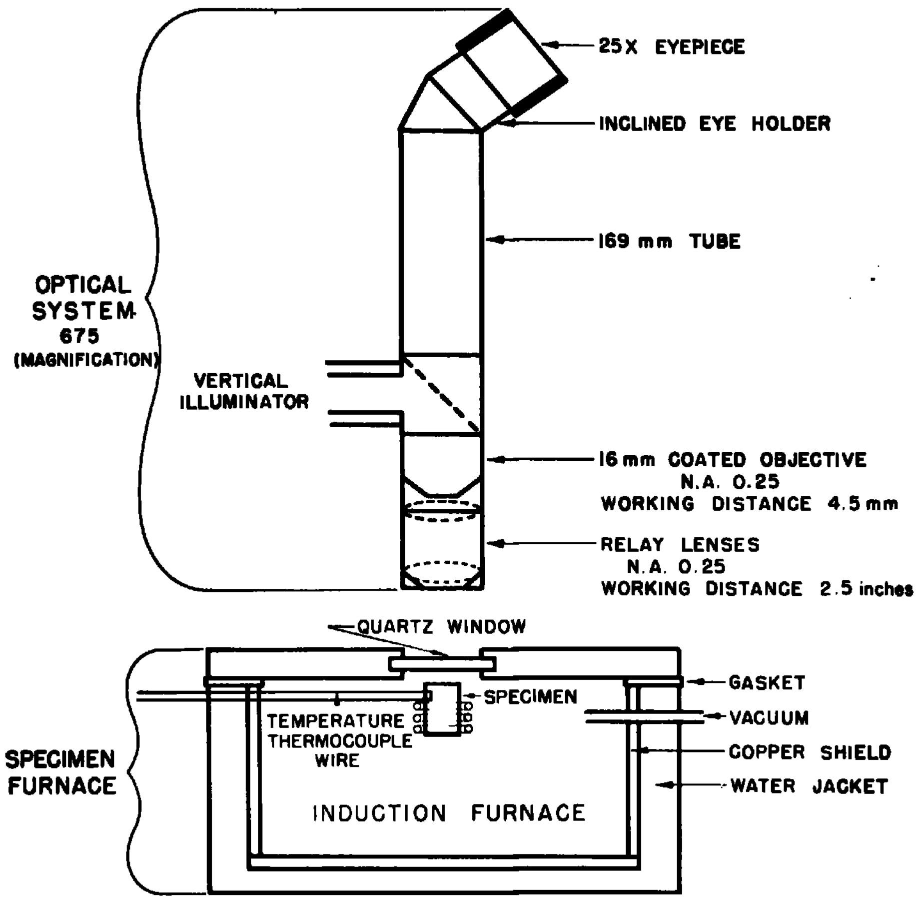

Figure 10. Proposed high temperature metaloscope.

ing medium. Specimens will be approximately ⅜-inch in diameter and the diameter and length of the specimen will be equal. Design of the furnace will be such that a vacuum can be maintained around the specimens. A quartz window will also be incorporated above the specimens so that the optical system now being developed may be used for metallographic observation during heating.

INSTRUMENTATION

A mathematical investigation was undertaken to determine the frequency response required from a pressure pickup in order to obtain satisfactory records. The theoretical pressure ratio as function of cycle time, obtained by J. K. L. MacDonald,* formed the basis of the calculations. It is shown as the dotted line in Figure 11. This cycle was analyzed by a Fourier series, and the solid line gives the result up to the fifth harmonic of the cycle frequency. It is seen that the difference between the two curves is quite small. It was also necessary to study the effect of that part of the cycle where the pressure ratio is essentially unity, since the length of this might cause other harmonics to become predominant. For this purpose the cycle was still more idealized as shown in Figure 12. A Fourier analysis of this cycle with r as parameter gave the ratio between the amplitude of the R-th harmonic and that of the first. It is shown for the first nine harmonics in Figure 13. It is seen that if r is less than 0.5, the amplitude of all harmonics higher than the sixth is less than 3 per cent of that of the first.

The fact that r must be less than 0.5 is not important since r, representing the inactive fraction of the cycle, will always be smaller than 0.5.

Consequently the conclusion was stated that a satisfactory pressure pickup should have uniform frequency response up to about six times the cycle frequency. This conclusion applies only to conventional pulse jets and need not apply to other experiments where rapid pressure variations occur.

Instrumentation in connection with the problem of gas-sampling was described under Combustion Studies.

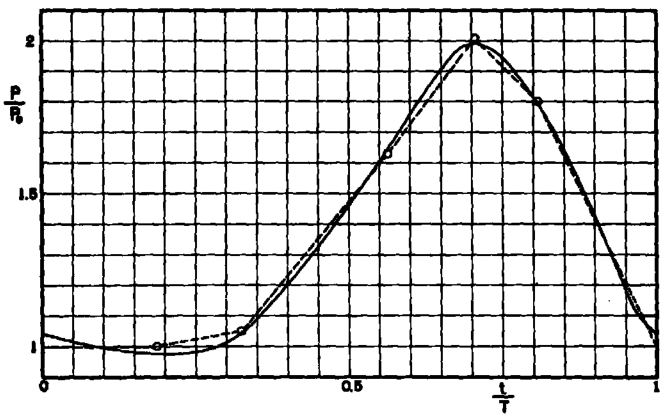

Figure 11. Theoretical pressure cycle of a pulse jet.

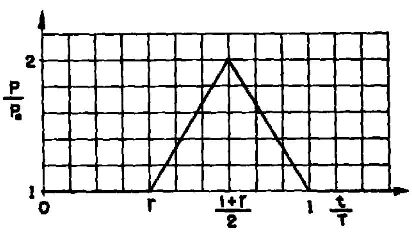

Figure 12. Idealized pressure cycle of a pulse jet.

* "A Gas Dynamical Formulation for Waves and Combustion in Pulse Jets." AMG, NYU No. 151, June 1946.

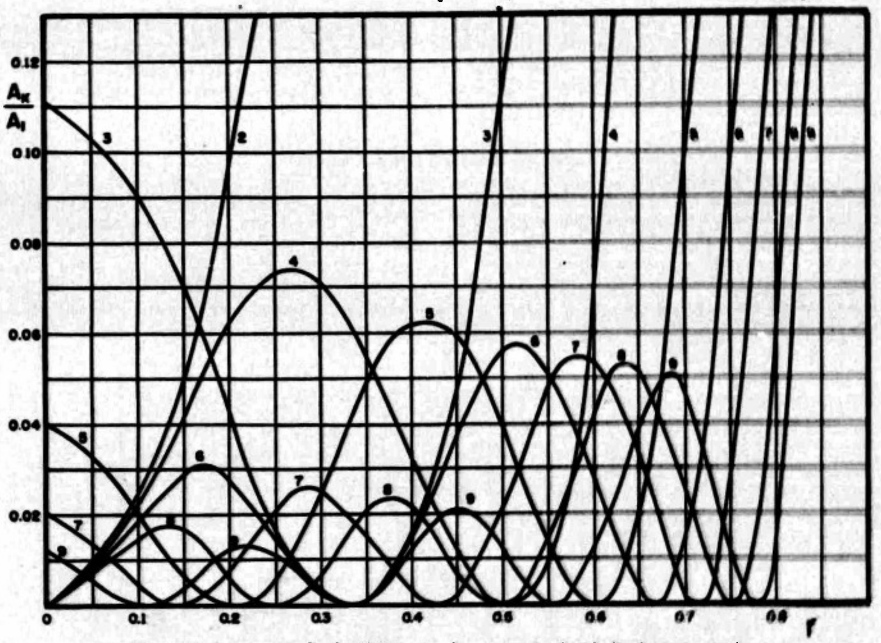

Figure 13. Relative amplitude of first nine harmonics for the idealized pressure cycle.

An Instrumentation Meeting was held in Buffalo on November 6th and was attended by representatives from the Aeronautical Engineering Department of Princeton University, the Institute of Mathematics and Mechanics of New York University, Engineering Research Associates, and Cornell Aeronautical Laboratory.

Informally discussed were instrumentation problems encountered in connection with Project SQUID for the measurement of pressure, temperature, thrust, flow, flame propagation velocity, turbulence and density, and gas-sampling. The discussion showed that most of the instrumentation questions will require more investigation and may form major research problems of their own. It was generally agreed at this meeting that the following two recommendations should be made to the SQUID Technical Committee.

1. A Symposium on Project SQUID should be held. This should not be restricted to instrumentation only but should include all phases. It is not advisable to have this meeting soon as most of the laboratories are only getting started. A final decision for this symposium will be postponed until the preliminary report on the activities of the various laboratories becomes available. Experts not directly connected with the project should be invited to report on special questions of possible interest.

2. Following the symposium it is suggested that a loose-leaf handbook on instrumentation be prepared to deal in compact form with all types of measurements encountered in Project SQUID. In general it should cover the field reported in the above discussion. Various laboratories could assume responsibility for selected problems and in this way the handbook could be kept up-to-date.

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ABSTRACT

Theoretical investigation of pulsejet revealed that shortening a combustion time would result in better performance. Two-dimensional diffuser models were wind-tunnel tested at Mach number 1.7. Schlieren photographs were taken of shock pattern. Combustion chamber was built to determine effect of turbulence under controlled conditions of temperature, air/fuel ratio, and pressure. Proposed high-temperature metaloscope for study of metals under vibration and fatigue was discussed. Further research program was outlined.

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ABSTRACT:

A preliminary summary is given concerning the fundamental research regarding liquid rocket and pulsejet propulsion. An attempt is being made to study the mechanism of a pulsejet by means of an analogous physican phenomena. As a result of a theoretical investigation of the pulsejet engine, it was concluded that shortening of the combustion time would considerably improve performance. Two-dimensional diffuser models have been tested in the wind tunnel at a Mach number of 1.7 and schlieren photographs have been made of the shock pattern. Investigation has been started to determine the influence of different parameters affecting the velocity of flame propagation, especially the influence of turbulence under controlled conditions of temperature, air/fuel ratio and pressure. Investigation of heat-resistant material for use as flutter valve is in progress. Supersedes ATI's - 4916 & 47585 & 70812

*Office of Naval Res., Washington, D. C.

DISTRIBUTION: Copies of this report obtainable from Air Documents Division; Attn: MCIDXD

DIVISION: Power Plants, Jet and Turbine (5) 2

SECTION: Combustion (4) 2

SUBJECT HEADINGS: Project Squid (75403); Engines, Pulse jet - Development (33988.2); Engines, Rocket - Development (34108.7)

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ABSTRACT:

A summary is given on work done on Project Squid since the beginning of the program. The work has been carried out under three phase assignments. Under this program, theoretical and wind tunnel investigations were to be conducted on flows and losses in diffuser inlets, diffusers, intake valves, exhaust nozzles, and thrust-augmenting ducts for subsonic and supersonic pulse-jet engines. Studies were to be made of the theory of combustion, the effect of turbulence on flame propagation and cooling, and existing theories were to be augmented by means of experimentation. Moreover, an experimental investigation of temperature and fatigue-resistant materials for intake valves and coatings should be made. This report gives information on the progress achieved sofar in these investigations.

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AIR TECHNICAL INDEX

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